Thermal, Electrical and Viscous (TEV) Characterization of Biomodified Geomaterials

A dissertation submitted by

Partha Narayan Mishra
(710ce1161)

in partial fulfillment of the requirements
for the award of the degree of

Bachelor & Master of Technology
(Dual Degree)
In
Civil Engineering
(Geotechnical Engineering)

Department of Civil Engineering
National Institute of Technology
Rourkela-769008, Odisha, India

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Under the supervision of

Dr. Sarat Kumar Das

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Dedicated to my parents

Mr. Prabhat Kumar Mishra (deceased)
&
Mrs. Mamata Rath

“In science, self-satisfaction is death. Personal self-satisfaction is the death of the scientist. Collective self-satisfaction is the death of the research. It is restlessness, anxiety, dissatisfaction, agony of mind that nourish science.”

–
Jacques Monod
Nobel laureate in Medicine

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26th May 2015

CERTIFICATE

This is to certify that the project entitled **'Thermal, Electrical and Viscous (TEV) Characterization of Biomodified Geomaterials'** submitted by Mr. Partha Narayan Mishra (Roll No.710CE1161) in partial fulfilment of the requirements for the award of Master of Technology dual degree in Civil Engineering (Geotechnical Engineering) at National Institute of Technology Rourkela is an authentic work carried out by him under my supervision and guidance. Further, I also certify that, this dissertation has not been submitted to any other institute or organization for the award of any degree or diploma.

Dr. Sarat Kumar Das
(Project mentor)

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I would like to take this opportunity to express my deepest sense of gratitude and indebtedness to the people who rendered their kind help directly or indirectly for the completion of the project entitled as '**Thermal, Electrical and Viscous (TEV) Characterization of Biomodified Geomaterials**'. Even with the help of a professional lexicographer, words in this acknowledgement page will never ever be able to touch the horizon of generosity of those who aided the current work in terms of guidance, suggestion and constructive criticism.

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Partha Narayan Mishra

Abstract

Biomodification serves as a means for alteration of inherent engineering properties of geomaterials using microbes. In this regard, the present investigation is devoted towards pre and post biomodification assessment of thermal, electrical and viscous (TEV) properties of several geomaterial specimens. The scope of the current research also includes establishing correlations among the above mentioned properties and other geotechnical parameters of the earth materials. To assist the study, a soil thermal probe, electrical probe and viscometer are designed and fabricated .The thermal probe (ThP) works on the principle of transient heating technique, and is preferred over the ones based on steady state measurements to eliminate the effects of moisture migration and to reduce the time lag in measurement. The electrical probe (EcP) is based on the principle of application of a constant regulated AC voltage across the sample, measurement of electrical current flow and subsequent calculations to assess electrical conductivity of the soil mass. A soil viscometer (GeoVM) is designed and fabricated for shear strength and viscosity appraisal of geomaterial slurries. Subsequently, these equipment are calibrated and used for estimation of the respective soil properties. A radiation resistant bacterial sp. featured in the study. Field application of this investigation applies to hazardous waste disposal systems and for suitability assessment of thermal backfills.

Keywords:
Tranisent needle probes; Soil Electrical probe; Soil viscometer; Biomodification

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List of Symbols and Acronyms

Symbols/ Acronyms	Meaning
TEV	Thermal-Electrical-Viscous
ThP	Fabricated soil thermal probe
EcP	Fabricated soil electrical probe
GeoVM	Fabricated soil viscometer
DGR	Deep Geological Repository
λ	Thermal conductivity of the material
$\frac{dQ}{dt}$	Rate of heat flow
A	Cross sectional area of the material normal to the direction of heat flow
$\frac{dT}{dx}$	Temperature gradient normal to the direction of heat flow
R	Resistance of the conductor
I	Applied current in the conductor
V	Established potential difference across the conductor
A	A constant dependent upon dimensions of the conductor
$\frac{1}{\rho}$, EC	Electrical conductivity of the material
T	Applied shear stress
η	Coefficient of viscosity
$\frac{dv}{dy}$	Velocity gradient
q_i	Rate of heat flow across unit area of the soil in i ($i = x$ or y or z) direction
λ_u	Thermal conductivity of unfrozen soil
λ_f	Thermal conductivity of frozen soils
W	Gravimetric water content
ρ_d	Dry density
λ_r	Thermal conductivity normalized with respect to degree of saturation
λ_{dry}	Thermal conductivity of dry soil
λ_s	Thermal conductivity of the saturated soil
Q	Electrical power input
Δx	Length of the sample
Δt	Temperature difference applied across the sample
A	Thermal diffusivity constant
R	Radial distance from source
S	Slope of the temperature change vs. natural logarithm of elapsed time.

$\Delta\theta$	Temperature rise
SAXBEY	Sand Bentonite mixture in the dry weight ratio of x:y
NB	Nutrient broth media
FESEM	Field Emission Scanning Electron Microscopy
EDX	Energy Dispersive Xray
GeoTherm	Thermal conductivity prediction model
GeoMoist	Soil moisture prediction model

Chapter 1

Introduction

1.1 Concept of thermal-electrical-viscous (TEV) characterisation of soil

Of all the thermal properties of the geomaterials, investigations pertaining to thermal conductivity have garnered appreciable amount of attention of the researchers in the recent past. Thermal conductivity of the encapsulating earthmaterial, determined either in-situ or in the laboratory scale, is used to numerically model the thermal migration either in steady state or in a transient manner through the soil mass, which forms the basis for design of barrier systems meant for disposal of hazardous wastes. The waste containing canisters are initially at higher temperature, and it is expected that the heat emanated from them dissipate quickly to the surrounding geoenvironment. This requires the host rock and the engineered backfill around the canisters to have higher value of thermal conductivity. Numerical modelling of thermal migration through engineered buffers requires thermal conductivity as an input parameter (Surya et al., 2014; Mishra et al., 2014).Study of thermal conductivity of soil is also vital for understanding the effect of cold, frost on soil used as a foundation material in roads, pipelines, airfields and buildings in cold regions. Frost heave or thaw can cause loss of stability and potential damage. Thus, rate and depth of freezing and thawing is taken into consideration by those associated with design of structures in countries predominantly experiencing cold climate (Farouki ,1981; Penner and Crawford, 1983). Thermal conductivity is also a significant variable regulating daily and seasonal variation in ground temperature (Penner and Crawford, 1983). Thermal properties of soil are also of importance while dealing with the problems in heat exchange at ground surface (Farouki, 1981). Stability of the earthmaterial by artificial cooling and heat extraction is often attempted to reduce permeability and improve strength. Knowledge of thermal properties of geomaterials is required here to ascertain the amount of heat to be removed and the rate at which frozen barrier is to be established (Sanger, 1968).During design of a centralised air conditioning system, where coolant carrying ducts has to run below the ground, it is necessary for the surrounding engineered soil mass to have lower value of thermal conductivity and act as an insulator to prevent heat loss from the coolant duct (Mahamaya et. al. , 2015). On the contrary, backfill around buried power cables has to have higher values of thermal conductivity to carry away the heat from the cable sheath so that it does not overheat.

Electrical properties of soil are often used to delineate the contaminated land (Larissa,1999; Seifi et al.,2010) .A generalized relationship between thermal and electrical resistivity of soil was put forth by Sreedeep et. al., (2004).

A soil paste theoretically has shear strengths of about 1.76 g/cm^2 and 200 g/cm^2 at liquid and plastic limits respectively. As the shear strength increases, the resistive force for flow to occur also increases. This leads to increase in viscosity.

1.2 Role of microbes in soil systems

Soil contamination and subsequent bio-environmental threats is one of the alarming problems that draws attention of agro-geotechnical engineers. Spill of oil, industrial, municipal, hazardous wastes etc. are among the dominant causes of soil contamination. In this context, bioremediation serves as a potential decontamination method. This technique uses microorganisms to destroy and immobilize the contaminants. The intrinsic metabolism and co-metabolism process of microbes involves catalysis of contaminant organic compounds. Essentially, organic compounds act as a source of carbons and electrons. Carbon assists in formation of live cells and electrons generate the requisite energy. Nitrogen and phosphorous are commonly used as nutrient media for the microbes. In order to accept the engendered electrons, sufficient amount of electron accepters (oxygen in aerobic condition; nitrate, manganese, sulphate, iron in anaerobic condition) need to be present. A decline in energy gain is usually observed as the surrounding environmental condition shifts from aerobic to anaerobic.

Microbes present in a particular geoenvironment contribute to the specific properties of the soil and advantages of the associated niche. For instance, bacteria present in the root nodules of the leguminous plants develop a symbiotic relationship with the host by helping in nitrogen fixation and, in return acquiring a habitation to survive.

Often, it is attempted to improve the desired microbial activities in a region by addition of specialized microbial strains. This method is usually referred as bioaugmentation.

Temperature dependent bacterial growth is a well-established concept that confirms 5ºC to 60ºC is the temperature range most suitable for bacterial culture. The growth rate vs. temperature plot follows a parabolic profile; growth rate increases with increase in temperature, reaches peak value at a given temperature and then deteriorates. Significant work has been done by Ratkowsky et. al., (1982) in this field. Increase in temperature favors mobilization of contaminants by inducing physical changes such as reduction in viscosity and evaporation of volatile impurities. Temperature also controls rate of associated chemical reactions.

The present investigation pertains to addition of a cultured microbial strain into geomaterials, and to observe the alterations associated with the thermal, electrical and viscous properties of the biomodified earthmaterials. Importance of this study can be appreciated while dealing with situations where heat migration through soil occurs.

1.3 Objective of the study

The present investigation is devoted to ascertain the changes in the thermal, electrical and viscous (TEV) properties of a set of geomaterials subjected to microbial modification. To aid the determination of the TEV properties, a soil thermal probe (ThP), a soil electrical probe (EcP) and a viscometer (Geo-VM) is developed. Pre and post biomodification assessment of the earthmaterial set is carried out with the developed instrument. Based on experimentally obtained data, simplified models are proposed to determine soil thermal conductivity and soil-moisture from the knowledge of their basic geotechnical properties. Additionally, the study also includes numerical modeling of thermal migration through the engineered soils using a commercially available finite element package. Objectives and scopes of the study may be summarized as the following,

- Development of soil thermal probe (ThP), soil electrical probe (EcP), soil viscometer (GeoVM), and pre & post TEV property assessment of a set of geomaterials.
- Development of predictive models for determination of soil thermal conductivity and soil moisture, & numerical modeling of thermal migration trough engineered geomaterials.

Chapter 2

Literature Review

2.1 General

This chapter elucidates the theoretical background required to address the need of the hour. Terminologies associated with the current work, previous attempts made by the researchers working in closely related areas to the present investigation, derivation of the governing partial differential equation for heat flow in soils and various predictive models for determination of thermal conductivity of geomaterials are granted a place in this chapter.

2.2 Terminologies

Thermal conductivity (λ) is defined as the quantity of heat that flows normally across a unit cross sectional area of a material per unit time when subjected to a unit thermal gradient along the direction normal to the surface. Evidently, the unit of thermal conductivity is Watt/m-$^{\circ}$C.

$$\frac{dQ}{dt} = \lambda A \frac{dT}{dx} \qquad \text{...1}$$

where,

$\frac{dQ}{dt}$=Rate of heat flow

λ=Thermal conductivity of the material

A=Cross sectional area of the material normal to the direction of heat flow

$\frac{dT}{dx}$=Temperature gradient normal to the direction of heat flow

Electrical conductivity $\left(\frac{1}{\rho}\right)$ specifies the ease with which migration of electrical current can occur through a material. It is the inverse of electrical resistivity (ρ), and is a material property. SI unit of electrical conductivity is Siemens/meter(S/m). For a conductor of length L and cross sectional area A, electrical conductivity is given by,

$$\frac{1}{\rho} = \frac{1}{R} \times \frac{L}{A} = \left(\frac{I}{V}\right) \times a$$

...2

where,

R=Resistance of the conductor

I=Applied current in the conductor

V=Established potential difference across the conductor

a=A constant dependent upon dimensions of the conductor

Viscosity provides a quantitative measure of resistance to flow. SI unit of coeffient of viscosity is Pa.s (Kg/s.m). Newton's law relates coefficient of viscosity to the shear stress, and can be expressed as below.

$$\tau = \eta \frac{dv}{dy}$$

...3

where,

τ= Applied shear stress

η= Coefficient of viscosity

$\frac{dv}{dy}$= Velocity gradient

2.3 Review of literature

Pioneering efforts towards development of the thermal needle probe was made by Stalhane and Pyk (1931), van der Held and van der Drunen (1949) . ASTM D5334-08(2008b) describes the use of a thermal needle probe for temperature measurement with passage of time. However, the probe is limited to temperature range $0^{o}C$ to $100^{o}C$ and fails when phase change is involved.

Hooper and Lepper (1950) have devised thermal probe for determining the thermal conductivity of the unsaturated sand. The temperature of the probe is measured with the help of thermistors, which are fixed to the inside wall of the probe. A series of tests were conducted on dry, unsaturated and saturated sand. An empirical equation has been developed for the variation of thermal conductivity of sand with its moisture content. It has been demonstrated that a sharp rise in thermal conductivity of the sand occurs as the saturation rises from zero to twenty percent and thereafter it remains practically constant (i.e. independent of the moisture content).

After an extensive review, Mitchell and Kao (1978) opined that among all the methods , thermal needle method, which works on the principle of transient method, is most efficient and simple to use. Another advantage associated with the transient method is that the thermal resistivity can be computed without estimating the specific heat of the material.

Ewen and Thomas (1987) came forward with a thermal probe and carried on a number of tests on dry, unsaturated and saturated sand. They proposed an empirical equation for the variation of thermal conductivity of sand with its moisture content. It has been demonstrated that a sharp rise in thermal conductivity of the sand occurs as the saturation rises from 0 to 20 percent and thereafter it remains practically constant.

Extensive long-term in situ experimentation was carried out by Mathur et al. (1993) to appraise the effect of heat on geomaterials in a 1000 m deep mine. The rock mass was heated with the help of electrical heaters and thermocouples have been used for measuring the rock mass temperature. Analytical solutions were derived based on Green's function. A FEM model was also conceived and the predicted results were well in agreement with the insitu test results.

With the aid of a fabricated probe that operates based on the principle of transient method Singh and Rao (1998) evaluated thermal resistivity of clay (black-cotton soil), silty-sand, fine sand and coarse sand. It has been verified that for a particular moisture content, the dry-density influences the thermal resistivity much more in the dry of optimum region as compared to the wet of optimum side and the thermal resistivity of soil is minimum, when moisture in the soil is close to the OMC.

Singh and David (2000) have proposed a computational algorithm (DDTHERM), which can be used, easily and efficiently, to estimate thermal resistivity of a multi-phase soil system. This algorithm incorporates different soil densities and moisture contents. An artificial neural network (ANN) for predicting soil thermal resistivity has also been devised based on the thermal resistivity values reported by Singh and Rao (1998). It has been reported that this neural network can be used quite efficiently to estimate soil thermal resistivity.

Arnepalli and Singh (2004) developed generalized relationship for determining thermal resistivity of various soils by knowing the dry density, moisture content and percent size fraction of the various particle sizes. Authors have studied the thermal resistivity of soils by fabricating a field thermal probe and validation of the proposed generalized equations have been done with the results available in the literature.

Rhoades and Schilfgaarde (1976) made use of an electrical conductivity probe for determination of soil salinity following the guiding principle of Wenner four electrode method (Halvorson et al., 1977).

Arulanandan (1991), Rao et al. (2007) used an impedance analyzer for measurement of dielectric constant k of various soils.

Fam and Santamarina (1997) measured dielectric permittivity of soils with a coaxial terminator probe integrated with a network analyzer.

Lee et al. (2002) measured capacitance of the saturated contaminated sands using impedance analyzer in the frequency range of 75 kHz to 12 MHz.

Sreedeep et al. (2004) developed an electrical resistivity probe and electrical resistivity box for measurement of electrical properties of soil. Calibration was done using standard NaCl and KCl solutions.

Yasutomi et al. (1967), Hajela et al. (1972) and several other researchers have made studies regarding measurement of soil properties with viscometers.

2.4 Governing Partial Differential equation for heat flow in soils

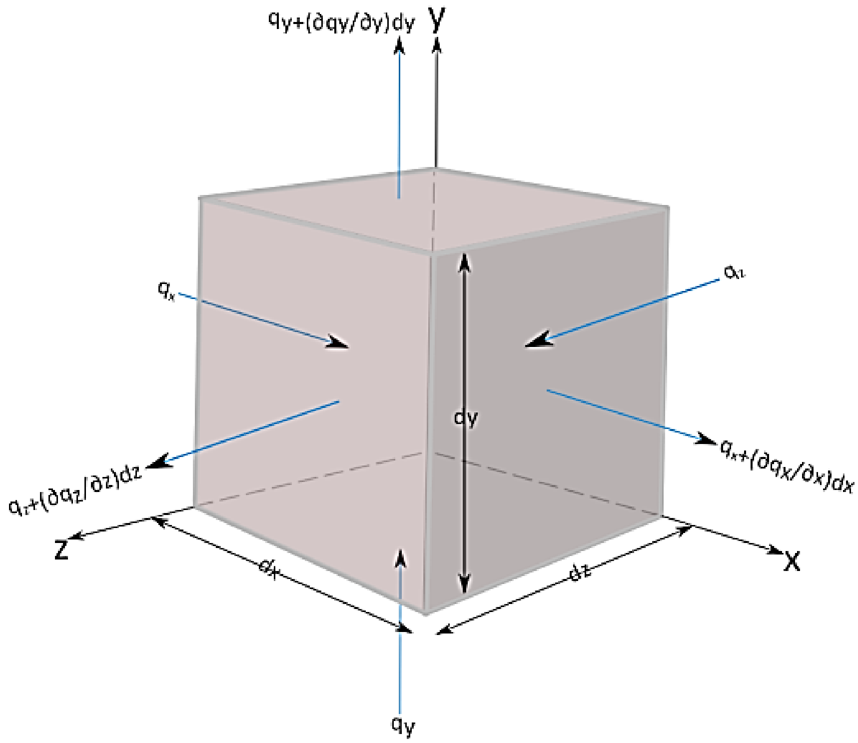

Figure 1: Soil block of volume $dx.dy.dz$

Referring to the figure furnished above , $dx.dy$ and dz stands for the dimensions of the element in x, y and z directions respectively. q_i gives the rate of heat flow across unit area of the soil in i $(i = x\ or\ y\ or\ z)$ direction. Using the principle of conservation of thermal energy and for steady state conditions,

Amount of heat flowing into the element=Amount of heat flowing out of the element

i.e.

$$\left(q_x + \frac{\partial q_x}{\partial x}dx\right) - q_x + \left(q_y + \frac{\partial q_y}{\partial y}dy\right) - q_y + \left(q_z + \frac{\partial q_z}{\partial z}dz\right) - q_z = 0$$

i.e.

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = 0$$

Employing Fourier's law of heat flow, the above equation gets modified as,

$$\frac{\partial\left(-\lambda\,{}^{\partial T}/_{\partial x}\right)}{\partial x} + \frac{\partial\left(-\lambda\,{}^{\partial T}/_{\partial y}\right)}{\partial y} + \frac{\partial\left(-\lambda\,{}^{\partial T}/_{\partial z}\right)}{\partial z} = 0$$

i.e.

$$\lambda\frac{\partial^2 T}{\partial x^2}+\frac{\partial\lambda}{\partial x}\frac{\partial T}{\partial x}+\lambda\frac{\partial^2 T}{\partial y^2}+\frac{\partial\lambda}{\partial y}\frac{\partial T}{\partial y}+\lambda\frac{\partial^2 T}{\partial z^2}+\frac{\partial\lambda}{\partial z}\frac{\partial T}{\partial z}=0$$

... 4

For transient analysis, net heat flux through an element needs to be equal to the change in heat storage with respect to time.
i.e.

$$\frac{\partial \mathrm{q_x}}{\partial \mathrm{x}}+\frac{\partial \mathrm{q_y}}{\partial \mathrm{y}}+\frac{\partial \mathrm{q_z}}{\partial \mathrm{z}}=\zeta\frac{dT}{dt}$$

Employing Fourier's law of heat flow, the above equation gets modified as,

$$\frac{\partial\left(-\lambda\,{}^{\partial T}/_{\partial x}\right)}{\partial x}+\frac{\partial\left(-\lambda\,{}^{\partial T}/_{\partial y}\right)}{\partial y}+\frac{\partial\left(-\lambda\,{}^{\partial T}/_{\partial z}\right)}{\partial z}=\zeta\frac{dT}{dt}$$

i.e.

$$\lambda\frac{\partial^2 T}{\partial x^2}+\frac{\partial\lambda}{\partial x}\frac{\partial T}{\partial x}+\lambda\frac{\partial^2 T}{\partial y^2}+\frac{\partial\lambda}{\partial y}\frac{\partial T}{\partial y}+\lambda\frac{\partial^2 T}{\partial z^2}+\frac{\partial\lambda}{\partial z}\frac{\partial T}{\partial z}=\zeta\frac{dT}{dt}$$

... 5

where,

ζ= Volumetric specific het (i.e. mass specific heat multiplied by density of soil)

The above equations are valid as long as the temperature of the soil is above freezing

2.5 Models for prediction of thermal conductivity of geomaterials

2.5.1 Kersten's empirical equations

This model was proposed by Kersten (1949) after an extensive study of thermal conductivity of more than 1000 soil samples. If λ_u represents the thermal conductivity of unfrozen soil, λ_f stands for the thermal conductivity of frozen soils , w denotes the gravimetric water content and ρ_d is used to describe dry density in g/cm^3 ,then the model can be summarized with the following equations.

For sandy soils

$$\lambda_u=0.1442[0.7log(w)-0.4]\times 10^{0.6243\rho_d}$$

and,

$$\lambda_f = 0.001096 \times 10^{0.8116\rho_d} + 0.00461w \times 10^{0.9115\rho_d}$$

...6

For fine grained soils

$$\lambda_u = 0.1442[0.9log(w) - 0.2] \times 10^{0.6243\rho_d}$$

and,

$$\lambda_f = 0.001442 \times 10^{1.373\rho_d} + 0.01226w \times 10^{0.4994\rho_d}$$

...7

2.5.2 Johansen's model

This model was given by Johansen in 1975, and it included the effects of mineralogy, degree of saturation during calculation of thermal conductivity. If λ_{ru} and λ_{rf} denotes normalized thermal conductivity in W/m.K for unfrozen and frozen soils respectively, S_u stands for the degree of saturation in decimal form then,

for sandy soils

$$\lambda_{ru} = 0.7log(S_u) + 1$$

and,

$$\lambda_{rf} = S_u$$

for fine grained soils

$$\lambda_{ru} = log(S_u) + 1$$

and ,

$$\lambda_{rf} = S_u$$

Thermal conductivity(λ) normalized with respect to degree of saturation (λ_r) is given by the following equation where λ_{dry} is the thermal conductivity of dry soil and λ_s is the thermal conductivity of the saturated soil. (W/m^{o}C)

$$\lambda_r = \frac{\lambda - \lambda_{dry}}{\lambda_s - \lambda_{dry}}$$

i.e.

$$\lambda = \lambda_r(\lambda_s - \lambda_{dry}) + \lambda_{dry}$$

...8

Limiting conditions are,

$$If\ S = 0, \lambda = \lambda_{dry}\ and\ \lambda_r = 0,$$

$$and\ if\ S = 1, \lambda = \lambda_s\ and\ \lambda_r = 1$$

Say, λ_{su} and λ_{sf} represent thermal conductivity of saturated unfrozen and saturated frozen soils respectively (W/m°C), λ_p,$\lambda_w$and λ_i stand for thermal conductivity of soil solids, water and ice respectively (W/m°C),n is the porosity of soil in decimal form, then

$$\lambda_{su} = \lambda_p^{1-n}\lambda_w^n$$

and,

$$\lambda_{sf} = \lambda_p^{1-n}\lambda_i^n$$

For compensating quartz content(q) expressed as a volume ratio referenced to solids portion,

$$\lambda_p = \begin{cases} 2.0^{1-q} \times 7.7^q, when\ q > 0.2 \\ 3.0^{1-q} \times 7.7^q, when\ q \leq 0.2 \end{cases}$$

2.6 Critical appraisal of literature review

The extensive literature review indicated that transient methods of soil thermal conductivity measurement are more preferred over steady state methods. Thermal needle probes operating based on the principle of transient heating are used by several researchers for estimation of thermal properties of soil. Electrical and viscous properties are easy to be measured using fabricated probes and viscometers. Further, this chapter included various soil thermal conductivity prediction models and governing differential equation for heat flow in soils which provided an opportunity to validate the present work and, give a fundamental idea for numerical modeling of thermal migration as in case of field problems.

Chapter 3

Methodology and Material Characterisation

3.1 General

This chapter depicts about the underlying principles, and the intricacies involved in the operation and fabrication of the soil thermal probe (ThP), soil electrical probe (EcP) and the viscometer (Geo-VM) intended to measure viscosity of the soil paste. Further, this chapter also grants a place to the characterisation of the geomaterials and the microbe under the scope of the present work.

3.2 Soil thermal probe (ThP)

3.2.1 Thermal conductivity measurement techniques

i. Steady state measurement

In this method, a thermal gradient is applied across the soil sample. When the temperature inside the soil stabilizes, the power required to maintain the thermal gradient is used to measure the thermal conductivity(λ) of the sample by employing the equation.

$$\lambda = Q/A \times \Delta x/\Delta t \qquad \ldots 9$$

where,

Q=Electrical power input
A=Cross sectional area of the sample
Δx=Length of the sample
Δt=Tempearture difference applied across the sample

However, it may take a long time to establish a steady state temperature inside the sample, which may lead to drying of the hot end accumulation of water or ice at the cold end of the sample. Moisture migration may result in inaccurate thermal conductivity measurement.

ii. Transient method

In this method, a thin thermal probe is inserted into the soil sample, which is supplied with a constant electric power, and variation of the probe temperature with time is recorded. Due to requirement of shorter testing time, this technique is less prone to moisture migration. During measurement of thermal conductivity employing the principle of transient method using the probe, the governing equation in cylindrical coordinates reads,

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \quad ...10$$

where,

α=Thermal diffusivity constant
r=Radial distance from source
T=temperature at time t

Temperature rise ($\Delta\theta$) measured by the probe within the time interval t_1 and t_2 may be given by,

$$\Delta\theta = \frac{Q}{4\pi\lambda}\ln\left(\frac{t_2}{t_1}\right) \quad ...11$$

where,

Q=Electric power input per unit length of the probe in W/m
Now,

$$\lambda = \frac{2.303 \times C_n Q}{4\pi S} = \frac{2.303 \times C_n VI}{4\pi S} = \frac{2.303 \times C_n I^2 R}{4\pi S} \quad ...12$$

where,

S=Slope of the temperature change vs. natural logarithm of elapsed time.

V=The applied voltage

I=Current in the probe

R=Resistance per unit length of the probe

The probe may be calibrated with a material of known thermal conductivity $\lambda_{water} = 0.607\frac{W}{m.K}$ at 25^0C , $\lambda_{glycerine} = 0.292\frac{W}{m.K}$]

$$\text{Calibration constant}(C_n) = \frac{\lambda_{material}}{\lambda_{measured}}$$

...13

where,

$\lambda_{material}$=Thermal conductivity of the known material

$\lambda_{measured}$=Thermal conductivity measured with the probe for the calibration material.

For transient analysis an infinitely long and thin heat source is required which is simulated by taking a probe of higher length to diameter ratio.

3.2.2 Fabrication details and working principle of ThP

Figure 2 presents the experimental setup for thermal conductivity measurement.

Figure 2: Experimental setup for the thermal probe (ThP)

3.3 Soil electrical probe (EcP)

Figure 11 shows EcP in operation.

Figure 3: EcP in operation

3.4 Soil viscometer (GeoVM)

Figure 4 shows the soil viscometer in operation.

Figure 4: GeoVM in operation

3.5 Material Characterisation

Geomaterials under the scope of the present investigation are red mud (NALCO), fly ash (JSPL), white soil (NIT campus), SA0BE100, SA80BE20 and SA70BE30.[1]

3.6 Microbial characterisation and culture

The bacterial culture under study is collected from MTCC (Microbial Type Culture Collection and Gene Bank), India. The desired nutrient media for the culture is nutrient agar (to be referred as NB for further instances). Required amount of nutrient media was added to the distilled water and then the culture media was autoclaved. The supplied sample holding tubes were broken in the laminar flow chamber, and the culture was transferred to test tubes containing the culture media. Figure 5 a-c exhibit the auto clave machine, prepared culture media in test tubes and spreading operation of the culture on the plate.

a b c

Figure 5: (a) autoclave apparatus (b) prepared culture media (c) Spreading the culture on plate

[1] SAxBEy refers to the mixture of IS grade III sand and bentonite in the dry weight ration of x:y

Gram staining confirmed that, the microbial strain is gram positive. This essentially means that, the microbe has peptidoglycan rich outer cell wall.

About 0.65g of nutrient broth (NB) was added to 50ml of distilled water, and then autoclaved (120^{o}C temperature & 30lb pressure) for about 15-20 minutes. After cooling, bacteria culture was transferred (inoculation) to the conical flasks carrying the culture media in the laminar flow chamber. The conical flasks are covered with cotton plugs, and are kept in BOD incubator at 30^{O}C for 48 hours, after which the grown microbial culture is added to the soil materials. The bio-treated geomaterials are kept overnight in room temperature and tested for thermal, electrical and viscous property assessment. Flow chart governing the organization of the present research can be found in figure 6

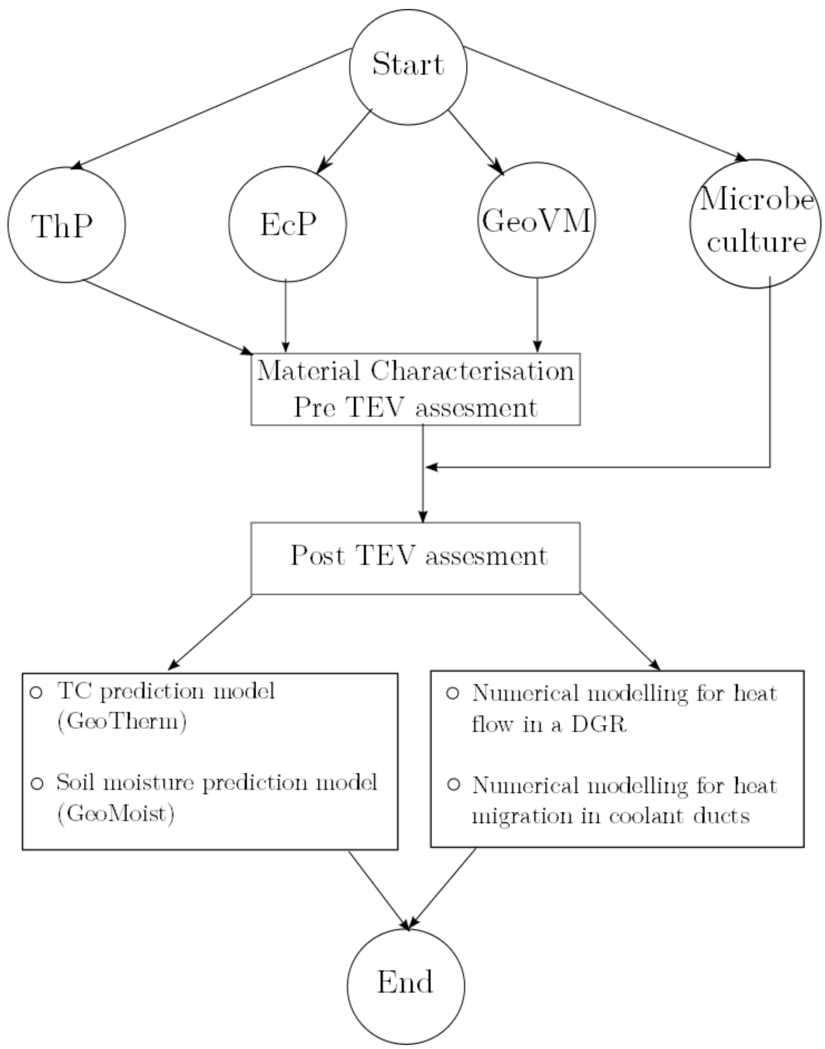

Figure 6: Flow chart dictating the present investigation

Chapter 4

Results and Discussions

This chapter covers the results obtained out of the extensive laboratory investigation on Thermal-Electrical and Viscous properties of the biomodified geomaterials. Please refer to the hard copy of the dissertation for further details.

Chapter 5

Numerical Modeling for Thermal Migration in Soils

5.1 General

This section depicts two practical geotechnical engineering problems dealing with thermal migration through soils. Thermal migration around an underground coolant carrying duct and a typical deep geological repository is explained in this chapter. Solutions to the governing differential equation are attempted using a commercially available finite element package, ANSYS™.

5.2 Thermal migration around an underground coolant carrying duct

The transient thermal numerical simulation is attempted using ANSYS which is a FEM based software package. A 2D model is realized where the coolant carrying PVC pipe is assumed to be buried at a depth a 2m from the ground surface. Schematics of the model geometry can be found from figure 7. This geometry is modeled in the ANSYS Workbench. Material assignment is done in the following step and mesh generation is carried out in the next phase. Figure 8 presents the generated mesh. An ambient temperature of 30^0C is established throughout the system apart from the surface of the PVC sheath, where the temperature is assumed to be 15^0C. Radiation losses are allowed from the surface of the earth and the coefficient of emissivity of the surface of earth is assumed to be 0.96. The governing differential equation 5 can now be solved with the assumed initial and boundary conditions with the help of Ansys solver. As a representative analysis, simulation is carried out for the geomaterial sample having a thermal conductivity of 0.18 W/m-K. The performance of the geomaterial sample as a thermally insulating barrier for the coolant system is carried out for a period of 1 year. It can be seen from figure 9 that the temperature at the interface of coolant sheath and the engineered backfill is reduced about 0.3 ^{0}C after a period of 1 year, which is acceptable from engineering point of view.

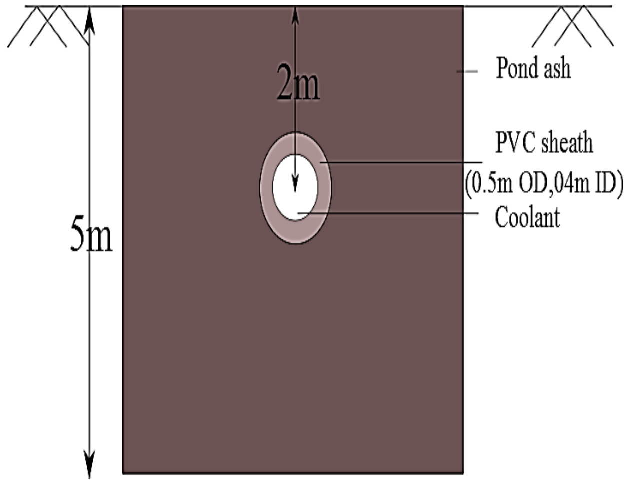

Figure 7: Schematics of the model geometry for the underground coolant duct system

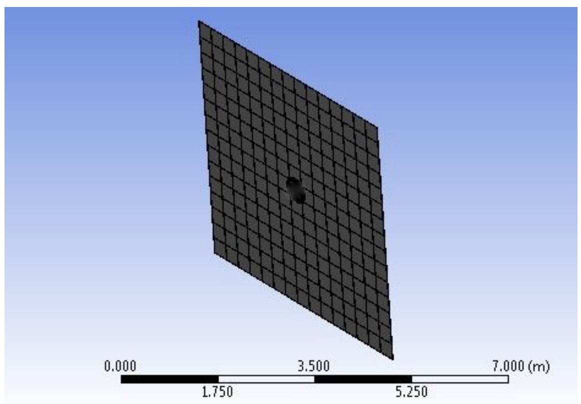

Figure 8: Generated mesh for the model

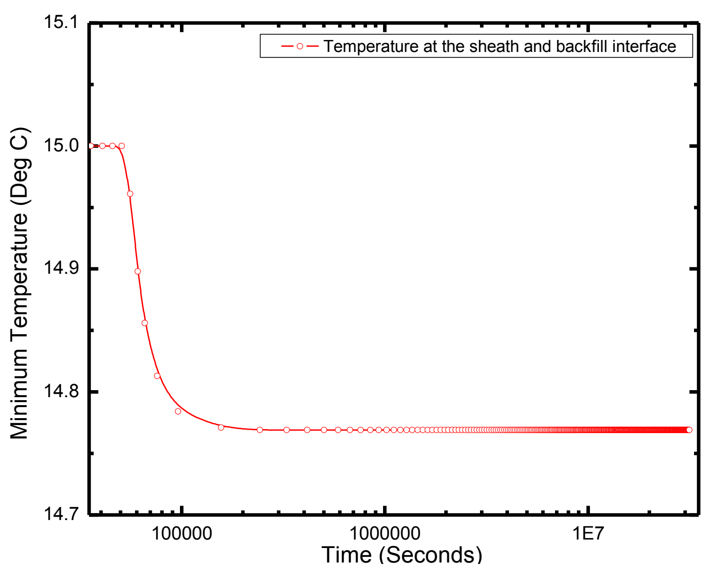

Figure 9: Temporal variation of temperature at the interface for a period of 1 year

5.3 Thermal migration around inside a typical deep geological repository

A deep geological repository (DGR) is intended for hazardous waste disposal at high depths below the ground surface. Waste carrying canisters at high temperature are placed at about 500-600 m depths from the ground surface. This will ensure that the radiation and heat will die down and will not affect the bio environment above. For this purpose, an engineered buffer around the canister is provided with higher value of thermal conductivity and lower value of hydraulic conductivity, which will allow rapid heat dissipation and less moisture migration. In the present problem, the canister is assumed to be at a depth of 498m below the ground surface. The steel canister is of length 4m and radius 0.625m. The encapsulating buffer has a radius of 1.25m, and has a thermal conductivity value of 1.80W/m-K. The host rock is assumed to be lime stone. Canister is at a temperature of 120^{O}C and the ambient temperature in the buffer and host rock is 38^{O}C initially. Figure 10 shows the modeled DGR in Ansys environment. Figure 11 illustrate the variation of temperature with time over a period of 200 years. It can be seen that, the temperature drops slowly and falls to about 60^{O}C at the end of transient analysis period.

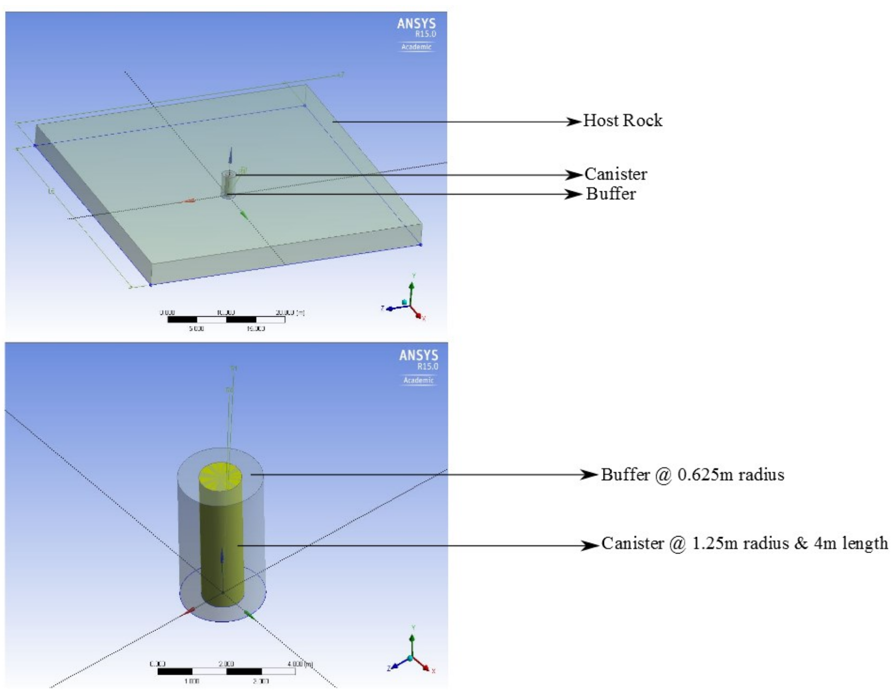

Figure 10: DGR modeled in Ansys environment

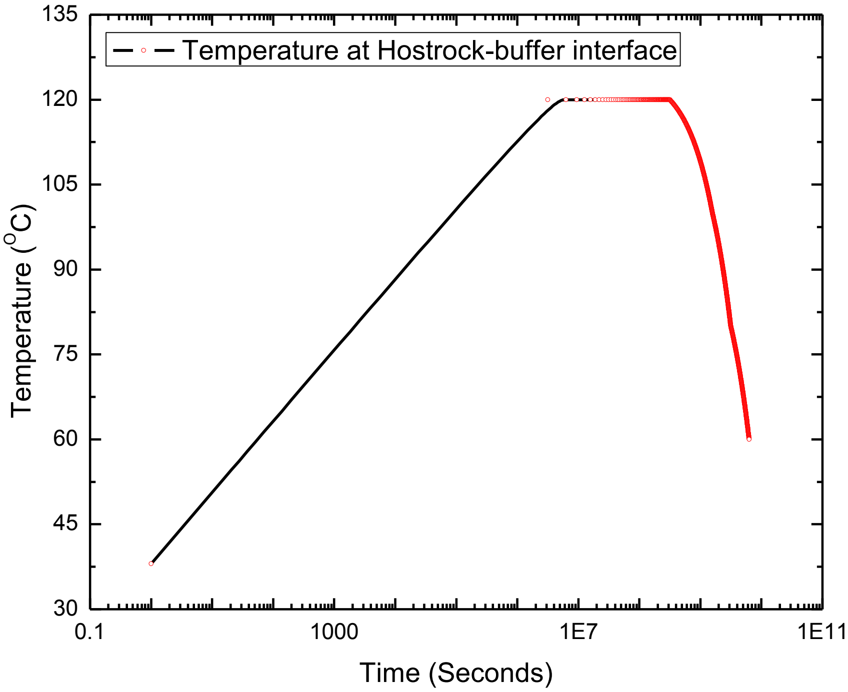

Figure 11: Temporal variation of temperature at the host rock-buffer interface for a period of 200 years

Chapter 6

Conclusions

6.1 Summary and conclusion

The present investigation dealt with assessment of thermal, electrical and viscous properties of several geomaterials. To achieve the objective, a soil thermal probe (ThP), a soil electrical probe (EcP) and a soil viscometer (GeoVM) was designed and fabricated. ThP works on transient heating technique; aided with a datalogger continuous temperature readings over time were taken. After calibrating ThP with standard glycerol of known thermal conductivity, the linear portion of the semi log plot between time and temperature in the geomaterial obtained using the ThP assembly helped to determine the thermal conductivity of the earthmaterial of interest. EcP works on the principle enumerated by Sreedeep et. al.(2004). EcP was calibrated with standard NaCl and KCl solutions, and was then used to estimate electrical conductivity of the geomaterials. Soil viscometer (GeoVM) is designed and fabricated. It is observed that, thermal and electrical conductivity of geomaterials increase with increase in degree of saturation and moisture content. Two predictive models namely GeoTherm and GeoMoist for estimation of thermal conductivity and moisture content of the soils respectively from their basic geotechnical parameters were developed, and were found to deliver satisfactory performance.

Numerical modeling of thermal migration around an underground coolant duct system and in a typical DGR was also covered under the purview of the present work. It is observed that an engineered backfill having lower thermal conductivity provided insulation properties, and heat migration gets hindered. Such backfills are desired to be provided around underground coolant ducts for preventing heat loss. An engineered buffer with high value of thermal conductivity fastens the heat dissipation process, and is of significance while dealing with thermal aspects during design of a DGR.

6.2 Scope for future work

The study can be extended to more number of geomaterials. There is still room for betterment and improvisation of GeoVM in terms of mechanical fabrication and motor selection. Viscosity measurement can be used as an alternate for consistency limit determination of the geomaterials. Numerical modeling can be done in a coupled manner where simultaneous heat and moisture migration takes place.

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